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STABILIZATION OF CLAY SOILS AGAINST EROSION LOSS

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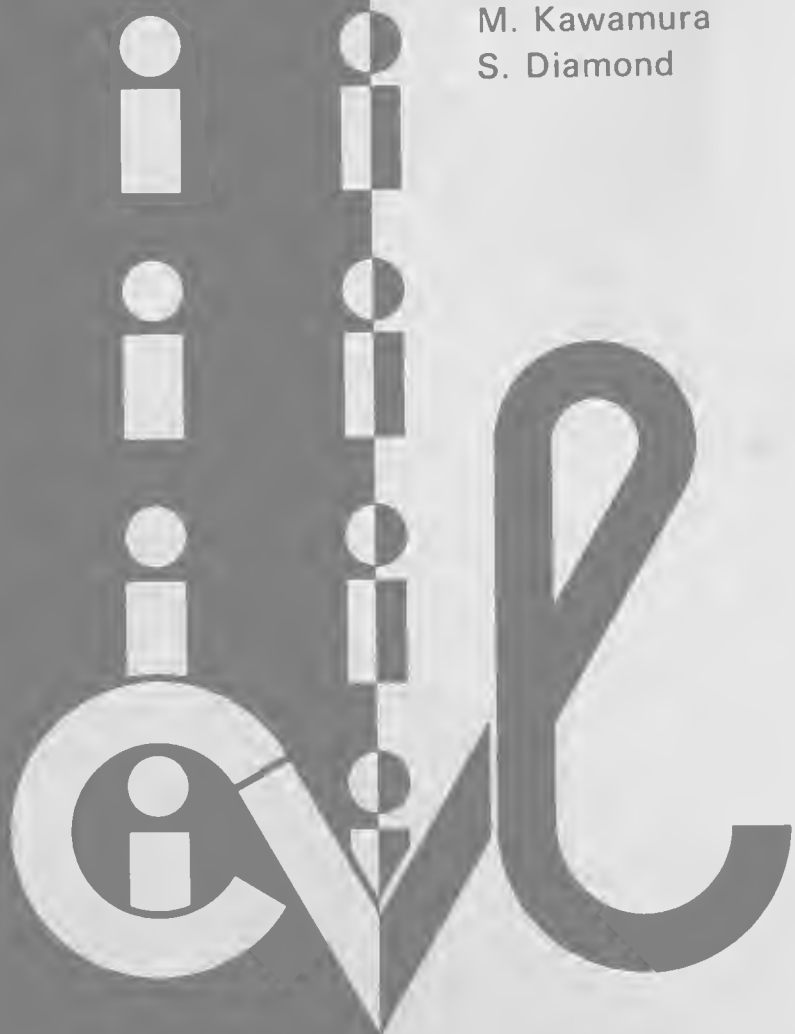

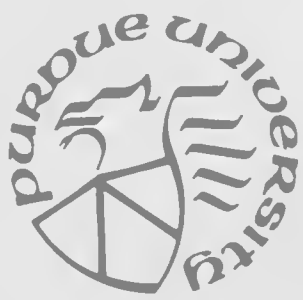

PURDUE UNIVERSITY
INDIANA STATE HIGHWAY COMMISSION

Technical Paper

STABILIZATION OF CLAY SOILS AGAINST EROSION LOSS

TO: J. F. McLaughlin, Director
Joint Highway Research Project

March 26, 1975

Project: C-36-50H

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 6-19-8

Attached is a Technical Paper titled "Stabilization of Clay Soils Against Erosion Loss" authored by Messrs. Mitsunore Kawamura and Sidney Diamond, Research Associates on our staff. The Paper is a summary of portions of the Interim Report dated August 28 on the HPR Part II Study "Soil Stabilization for Erosion Control". This Report has been accepted by all agencies concerned and hence acceptance of this Technical Paper is not required.

The paper is planned for publication by Clays and Clay Minerals. It is presented to the Board for information and approval of such publication if accepted by the publisher. The paper will also be forwarded to ISHC and FHWA for information and any comment they wish to make.

Respectfully submitted,

Harold L. Michael

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Associate Director

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16. Abstract

Accelerated soil erosion from construction sites and the resulting increase in downstream sediment load constitutes a significant environmental problem. Laboratory studies indicate that small percentages of hydrated lime or of Portland cement will stabilize clay soils against rainstorm erosion by preventing particle detachment. Coordinated measurements of the size distribution of water-stable aggregates, of pore size distribution by mercury porosimetry, and of microstructure by scanning electron microscopy and energy dispersive x-ray spectrometry were used to clarify aspects of the mechanisms responsible for the development of erosion resistance. Attainment of such resistance was marked by aggregation of a significant part of the clay into water stable aggregations of the order of several millimeters in size, and of minimal change in porosity and pore size distribution on exposure to the test rainstorms. At least some of the clay particles in the aggregations appeared to be partly converted to calcium-bearing reaction products, and formation of the "reticulated network" variety of calcium silicate hydrate gel linking adjacent particles was demonstrated.

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Technical Paper

STABILIZATION OF CLAY SOILS AGAINST EROSION LOSS

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Purdue University
West Lafayette, Indiana
March 26, 1975

STABILIZATION OF CLAY SOILS AGAINST EROSION LOSS

Mitsunore Kawamura* and
Sidney Diamond**

ABSTRACT

Accelerated soil erosion from construction sites and the resulting increase in downstream sediment load constitutes a significant environmental problem. Laboratory studies indicate that small percentages of hydrated lime or of Portland cement will stabilize clay soils against rainstorm erosion by preventing particle detachment. Coordinated measurements of the size distribution of water-stable aggregates, of pore size distribution by mercury porosimetry, and of microstructure by scanning electron microscopy and energy dispersive x-ray spectrometry were used to clarify aspects of the mechanisms responsible for the development of erosion resistance. Attainment of such resistance was marked by aggregation of a significant part of the clay into water stable aggregations of the order of several millimeters in size, and of minimal change in porosity and pore size distribution on exposure to the test rainstorms. At least some of the clay particles in the aggregations appeared to be partly convèrted to calcium-bearing reaction products, and formation of the "reticulated network" variety of calcium silicate hydrate gel linking adjacent particles was demonstrated.

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INTRODUCTION

Accelerated soil erosion from construction sites during the period that such areas are denuded of their natural vegetative cover before permanent pavements, water-channeling structures, and grass or other vegetative plantings are provided, represents a serious environmental problem in many localities (Younkin, 1973; Thronson, 1971; Thronson, 1973; Roberts, 1974, etc.). The present report represents work done in a project aimed at developing expedient and relatively inexpensive means of preventing such accelerated erosion. The methods explored involve incorporation of small amounts of known soil stabilizers, principally hydrated lime (calcium hydroxide) or Portland cement. In order to evaluate the effectiveness of such treatments, rainfall simulation equipment was designed with the specific capability of testing resistance to erosion of large numbers of specimens of soil stabilized in various ways. Full details of the design, construction, and operating characteristics of this equipment were provided by Diamond and Kawamura (1974). This equipment was used to evaluate the resistance of test stabilized soils to erosion arising from the impact of raindrops delivered in a standard test rainstorm sequence. The present paper reports the results of some of these tests, together with the results of investigations aimed at clarifying the mechanism by which the erosion resistance is conferred.

It should be noted that the results obtained do not necessarily reflect the ability of the stabilized soils to resist erosion caused by running water over steep slopes, a situation in which channeling and

rill formation often occur. However, it has been established by Young and Wiersma (1973) that soil detachment due to raindrop impact is the major cause of erosive loss in sheet erosion.

MEASUREMENT OF EROSION RESISTANCE

The simulated rainfall equipment was designed to deliver a rainstorm of controlled intensity (3½ in. per hour) to a group of three replicate soil specimens. These were compacted in 4 in. diameter molds and mounted in specially designed holders maintained at an angle of 5^{o} to the horizontal to permit free runoff of water. A rainfall applicator provided with more than 400 individual drop formers spaced 1.2 in. apart in a triangular array produced drops averaging 0.012 in. (0.3 mm.) in diameter delivered uniformly over the soil specimens. Calculations indicated that the energy delivered was more than 80 percent of that delivered by a natural storm of the same intensity. The standard erosion test sequence adopted consisted of the application of 3½ in. of simulated rainfall in one hour, a delay of 23 hours, and then a second 3½ in. application in one hour. The amount of rainfall actually delivered was checked each time by raingauges positioned among the soil containers.

Provision was made to collect all of the runoff from each specimen, and the soil removed was recovered, dried, and weighed to provide a direct assessment of erosion loss. The losses for the three replicate specimens were averaged, and expressed as weight of soil removed per square cm. of specimen surface. In practical terms a 1 gram/cm^2. loss corresponds to about 45 tons of soil lost per acre.

In general it was found that reproducibility of results between individual replicate specimens was satisfactory, and that erosion loss was reasonably consistent from test to test. The overall coefficient of variation measured in a special test series was less than 7 percent.

MATERIALS AND SPECIMEN PREPARATION

The results reported here were derived using two different soils, three different stabilizing materials, several levels of stabilizer addition, and curing periods ranging from 1 day to 28 days prior to exposure to the test rainstorm sequence. One of the soils was a B-horizon material derived from a member of the Crosby series, (a till-derived soil with a clay fraction containing montmorillonite, some mixed-layer clay, and kaolinite); this material has been characterized extensively in various soil mechanics research studies emanating from Purdue University. The other soil was the well-known "grundite" illite-bearing commercial clay* commonly employed as an experimental material in many laboratory studies. The stabilizers included two varieties of hydrated lime: an analytical reagent grade**, and a rather poor commercial hydrated lime which was found to be partly dolomitic and somewhat carbonated; and a conventional Type I Portland cement of normal composition.

The specimen preparation procedure involved blending of air-dried soil and stabilizer for 15 minutes in the dry state, followed by addition of water in the form of a fine spray, both processes being carried out

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* Illinois Clay Products Co., Lansing, IL.

** Mallinckrodt AR grade.

in a Patterson-Kelley twin-shell solid liquid blender. The amount of water added was that previously determined to yield the Standard Proctor optimum moisture content for the specific soil, 19 percent by weight for the Crosby and 20 percent by weight for the grundite. The moist soil-stabilizer-water mixes were then compacted using the standard Proctor hammer in specially fabricated split molds 4 in. in diameter and 1 in. high. The number of blows applied was that calculated to deliver the same applied energy per unit volume as is delivered in the standard Proctor compaction method (ASTM Designation: D 698-70, Method A). The compacted specimens were then sealed in plastic sacks and cured in a fog room at 74° F. for the desired period prior to commencement of the erosion test sequence. The surface exposed to the test rainstorm was the original bottom surface of the specimen, not the surface formed by trimming the directly impacted layer.

RESULTS

Erosion Loss of Unstabilized Soils

It was found that compacted but otherwise unstabilized Crosby soil lost 2.1 g/cm^2 of exposed soil in the standard rainstorm test sequence, while the corresponding grundite specimens lost an average of 1.7 g/cm^2. These losses, corresponding to the order of 90 tons/acre, indicate the intensity of the test rainstorm sequence.

The appearance of the residual surface of the Crosby soil is indicated in Figure 1A. The soil particles are clearly dispersed, little residual aggregation being apparent. Individual sand and

gravel sized grains are visible and are free of adhering clay particles, the latter having been washed away. In the grundite soil the surface after rainstorm exposure appears somewhat different, and was characterized by residual small scale aggregations of clay particles and greater topographic relief.

FIGURE 1 (A, B, C, D)

Effectiveness of Portland Cement in Reducing Soil Erosion

The effectiveness of Portland cement treatment in reducing erosion with Crosby soil is indicated in Fig. 2, in which soil lost in the standard rainstorm test sequence is plotted against curing time, for specimens treated with 2.5 percent and with 1 percent cement by weight of soil. It is apparent that the 2.5 percent treatment effectively and rapidly stabilizes Crosby soil, a 1-day curing period being sufficient to achieve almost zero soil loss. Treatment with 1 percent cement is effective, but only after a somewhat prolonged curing period of 28 days. After 7 days of curing the soil loss recorded was still about half that of the additive-free control specimens.

FIGURE 2

The appearance of the specimens treated with 2.5 percent cement and cured for 1 day after rainfall exposure is indicated in Fig. 1B.

Most of the original exposed surface of the specimens has been retained, soil loss being confined to a few patches and parts of the rim area. It should be understood that these specimens, despite the shiny surface appearance, were in no sense converted to a solid pavement; they remain highly permeable and have only modest strengths.

The appearance of the residual surface of specimens that were inadequately stabilized (i.e., those receiving too little stabilizing agent or insufficeient curing time) is typified by Fig. 1C. All of the original surface of the specimen has been eroded away. The appearance of the residual surface exposed at the conclusion of the test rainfall sequence suggests that while some dispersion of the particles had taken place, dispersion was incomplete and the exposed sand and gravel particles remain coated with a layer of partly cemented clay.

The results of the attempt to stabilize the grundite clay with 2½ percent of Portland cement were less than satisfactory, as indicated in Fig. 3. It appears that, at least at first, the effect of the "stabilizer" was to increase, rather than reduce, the amount of soil lost in the test rainstorm sequence. Additional curing brought only modest improvement, and even after 28 days the treated clay lost almost as much material eroded away as the untreated control specimens.

FIGURE 3

Clearly 2½ percent of cement was inadequate to stabilize grundite, and a second test series incorporating 5 percent cement was initiated.

Here again, the effect after 1 day of curing was that the erosion loss was worse than the control; but by 3 days of curing the effect was reversed and reasonably successful stabilization was attained, as is indicated in Fig. 3. As will be discussed subsequently, the relatively high percentage of cement required to properly stabilize grundite is matched by a similar high requirement of this soil for hydrated lime. This requirement seems not to be a reflection of the high surface area (around 85 m^2/g) or of the high clay content (around 60 percent by weight), but rather of the extremely acidic character of this clay, which is treated with strong acid in the commercial processing of the material. The measured pH of 1:1 clay - deionized water slurries was in the range 2.7 to 2.9.

Effectiveness of Hydrated Lime in Reducing Soil Erosion

The effeetiveness of hydrated lime in reducing the erosion loss of Crosby soil in the test rainstorm sequence is indicated in Fig. 4.

FIGURE 4

Treatment at the 1 percent level resulted in a decrease of erosion by more than a factor of 3 after one week of curing. Subsequent curing improved the erosion resistance, but only marginally. At the 2½ percent treatment level the effectiveness was considerably improved, the soil loss after 21 days being an insignificant 0.07 g/cm^2 of exposed surface. It is clear that hydrated lime, while not as rapid in its action as Portland cement, still is a potentially valuable stabilizer against rainstorm erosion.

An indication of the surface appearance of the Crosby soil stabilized with lime is given in Fig. 1D, the specimen pictured being one of those treated with 2½ percent lime and cured for 7 days prior to exposure to the test rainstorm sequence. While only part of the original specimen surface was retained, it appears that the soil is hardly dispersed, and again large sand and gravel grains are not washed free of the stabilized clay particles. The permeability of lime-stabilized specimens resembles that of the corresponding cement-treated soils, and the stabilized material again has only modest mechanical strength.

The results of attempts to stabilize the highly acidic grundite clay with hydrated lime were less happy. It was expected that a relatively high lime concentration would be required to overcome the acidity of the clay, and it was found that reagent grade calcium hydroxide added at the 5 percent level was quite satisfactory, reducing the erosion loss to about 0.2 g/cm^2 of exposed surface after 7 days of curing. However, with the impure partly dolomitic carbonated lime, success was not attained even at the 5 percent treatment level. In fact, the erosion losses of the treated samples were greater than that of the original clay, rising to 2.2 g/cm^2 after 1 week of curing and to almost complete loss of the clay (2.7 g/cm^2) after two weeks of curing. It was obvious that these treated clay specimens were completely dispersed under the beating action of the test rainstorm sequence.

Influence of pH on Stabilization

The influence of hydroxyl ion concentration (pH) of the pore fluid on soil stabilization processes has been appreciated for some time, particularly with respect to lime stabilization. Eades and Grim (1966) developed a quick test to determine the level of lime treatment necessary to mechanically stabilize a particular soil. This consisted of measuring the pH of a series of soil-lime-water slurries to determine the minimum lime content necessary to generate a pH of 12.4 (i.e. that of saturated lime solution). Evaluation of the test in terms of the unconfined compressive strength of stabilized soils produced by mixtures generating various pH levels was carried out by Thompson and Eades (1970). They concluded that the test conservatively indicates the lime required to produce effective stabilization in terms of the development of mechanical strength.

Stabilizing soil for the purpose of resisting erosion by raindrop impact presumably does not set as stringent a requirement as stabilization to develop mechanical strength for use in a highway subgrade; thus the pH 12.4 requirement is undoubtedly more conservative than necessary for present purposes. In the writers' experience, pH values of the order of 11.5 appear to indicate that sufficient lime or cement has been used for resistance to raindrop impact erosion to develop.

As mentioned earlier, the pH of a grundite slurry was only about 2.7, far lower than the normal range for natural soils. A 1:1 slurry of Crosby soil and water produced a measured pH of 5.6. It was found that pH values measured with slurries of both soils with 5 percent of

reagent grade calcium hydroxide by weight of soil added was of the order of 11.5, and increased slightly with aging. An explanation for the failure of the impure commercial lime to stabilize the grundite soil became apparent when it was found that a corresponding slurry generated an initial pH of only 8.0. Even after 24 hours, the pH had increased to only 10.4. On the other hand, with the more nearly normal Crosby soil, slurries made with this lime reached a pH of 11.5 after 1½ hours of standing.

While the failure of the commercial lime to stabilize the grundite clay can be understood in terms of the insufficient pH attained, additional insight is required to explain the fact that when treated with this lime the clay was actually de-stabilized, i.e. significantly more soil was lost than was lost by the untreated clay. It is believed that this too is a pH-dependent response. The untreated acid clay is in fact strongly acid flocculated, and the dried flocs possess some resistance to dispersion and removal under the raindrop impact. Increasing the pH to the 8 to 10 range undoubtedly destabilized these flocs, while at the same time it did not permit sufficient chemical reaction between clay particles and calcium hydroxide to generate effective lime stabilization.

In Fig. 3 a similar effect seems to be observed with the inadequate level (2½ percent) of Portland cement. Here too, it appears that the pH of the clay stabilizer mixture is high enough to lose what benefit the dried acid flocs can provide without at the same time providing sufficient cementation to offset the loss.

Effect of Stabilizers on Water-Stable Aggregate Size Distributions

Measurements of size distributions of water stable aggregates were carried out by wet sieving (Yoder, 1960; Kemper and Chepil, 1965). It was found that successful stabilization as indicated by the measured resistance to the standard rainfall sequence was correlateable with large increases in the content of water stable aggregations in the size ranges above 0.5 mm. Examples of such increases are shown in Fig. 5, for Crosby soil treated with 2½ percent lime and cured for various periods, and Fig. 6 for grundite stabilized with 5 percent Portland cement and cured for up to 7 days. In contrast, Fig. 7 indicates that grundite treated with 2½ percent cement but not successfully stabilized (as indicated in Fig. 3) did not form significant volumes of water stable aggregations.

FIGURE 5, FIGURE 6, FIGURE 7

Attempts to correlate the "aggregation index" (Kemper and Chepil, 1965) with resistance to erosion did not lead to any consistent pattern or relationship, although some weak association between the two variables undoubtedly existed.

Pore Size Distributions

Determinations of the pore size distributions of a number of specimens was carried out using conventional mercury intrusion

technique (Diamond, 1970A). Specimens were dewatered by oven drying at 105° C prior to mercury intrusion; in consequence the results reflect any changes in pore structure taking place during this drying process.

In general it was found that only minor differences were exhibited between soils compacted without stabilizers and the same soils compacted with the modest stabilizer contents employed.

However, it was instructive to compare these pore size distributions with those of small specimens recovered from the residual surface regions of the samples that had undergone exposure to the test rainstorm sequence. An illustration of such a comparison is provided in Fig. 8. Additive-free Crosby soil, after compaction and oven drying, showed a total porosity

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FIGURE 8

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available to mercury (at pressures up to 15,000 psi) of about 0.18 cm^3 per gram of soil. Most of this space was indicated as being in pores of diameters between about 10 μm and about 0.3 μm. Specimens prepared from the exposed surface region of the same untreated soil after rainstorm exposure and partial erosion showed a similar distribution, but with an increase in total pore space intruded from 0.18 cm^3 to 0.22 cm^3 per gram of soil. Most of the increase was in pores larger than 5 μm. This may represent pore space created by washing out some of the less stable naturally-occurring aggregations at the surface, or it may be an effect of whatever swelling might have taken place. Fig. 8 also shows a distribution curve for the residual surface zone of a stabilized Crosby soil (2½ percent lime, 7 days of curing) after exposure to rainfall.

It is apparent that this distribution is essentially the same as that of the "before exposure" specimen of untreated soil, except for a modest increase in the content of fine pores that is presumably associated with the reaction product formed between lime and the soil. The important feature of the distribution curve is the lack of significant alteration traceable to the rainfall exposure itself. Apparently properly stabilized soils, although they may erode slightly, do not undergo significant microstructural change under the beating action of the raindrop impact.

Porosimetry measurements provided some additional insight into the "destabilization effect" exhibited by grundite soils treated with inadequate amounts of quality of stabilizer. It was found that additive-free grundite soil exhibited virtually the same pore size distribution before exposure to rainfall that the residual surface zone exhibited after such exposure, indicating that there was comparatively little breakdown of the acid-stabilized aggregation units. However, as indicated in Fig. 9, the same was not true for grundite "destabilized" by treatment with 2½ percent Portland cement and cured for 14 days. Here the surface zone left after rainfall exposure showed a large increase in pore space intruded (0.19 cm^3 as compared with 0.13 cm^3 per gram of soil), and a clear indication that this increased pore space is in large pores - tens of μm in diameter. Such a pattern is consistent with breakdown of preexisting aggregations associated with the change in pH from a highly acid condition to a moderately alkaline one.

The untreated Crosby soil, being far less acid than the grundites undergoes some microstructural breakdown on exposure to the rainstorm

sequence, as indicated earlier. Presumably this represents the more nearly normal state of affairs with most soils, and the response of the grundite is to be considered unusual.

Scanning Electron Microscope Observations

A series of investigations was carried out using a Jeol SMU-3 scanning electron microscope (SEM) equipped with an EDAX International energy-dispersive x-ray analyzer (EDXA) to attempt to document morphological detail of the grundite and stabilized grundite materials in various conditions. As indicated in Fig. 10A and 10B, the surfaces of additive-free grundite specimens at the start of the rainstorm had a relatively smooth partial "skin" of oriented clay particles; the skin was incomplete, and there are open areas as indicated in Fig. 10B with a loose collection of individual unoriented clay particles and some small aggregations. There is an underlying structure of coarse aggregations that makes up the bulk of the specimens which is not visible at the uneroded surface. However, when the surface is exposed to rainfall, the skin is rapidly eroded away and the underlying structure of the aggregations is exposed, as is indicated in Fig. 10C. In process of erosion of additive-free grundite these tend to be broken down only slightly to smaller sizes, and removed without dispersion. However, when the clay is inadequately treated with a stabilizing agent and "destabilized", there is a continuing breakdown of these aggregations into smaller clusters and ultimately individual particles. A micrograph of a portion of the residual eroded surface of a grundite specimen inadequately stabilized with 5 percent of the impure commercial lime and

cured for 6 days, as shown in Fig. 10D, yields some indication of this breakdown especially in the lower portion of the figure.

Grundite specimens stabilized with Portland cement apparently retain the smooth but incomplete surface skin characteristics of additive-free grundite specimens, at least before exposure to rainfall. Well stabilized specimens properly cured before exposure show only small areas on the surface from which material is removed, but the skin undergoes a dramatic change of morphology. Fig. 11 shows the surface of a residual flat area of a specimen of grundite stabilized with 5 percent Portland cement, cured for 7 days, and examined after exposure to the test rainstorm sequence. The surface now has an incomplete layer of angular, blocky particles several μm in size, and

FIGURE 11

some rounded particles of similar size; some of the particles show distinct holes of unknown origin. EDXA examination of two typical grains, marked "A" and "B" in the micrograph, reveals that the former, rounded grain has prominent peaks for silicon at 1.71 keV, aluminum at 1.45 keV, and smaller ones for potassium at 3.3 keV, calcium at 3.7 keV, and iron at 6.4 keV. The chemical composition is clearly compatible with that expected for a partly reacted illite clay particle or aggregation of particles, and that is what must be present here. In contrast, the blocky grain at "B" shows only calcium peaks, and is almost certainly a crystal of calcite (calcium carbonate) formed from reaction with

hydrated lime deposited in the cement hydration reaction. Indications that this is so were obtained from x-ray diffraction powder patterns secured from powder scraped from the surface layer of this specimen. Calcium carbonate was found to be absent from the x-ray pattern of a companion specimen not exposed to the rainstorm, but calcium hydroxide peaks were detected. Presumably the wet condition obtained during and subsequent to the test rainstorm sequence facilitates the conversion.

While blocky calcite crystals have been found in eroded portions of similar specimens and, after some period even on fracture surfaces not directly exposed to the rainfall, it is not thought that these contribute significantly to the stabilization process. Of far greater consequence is the generation of calcium silicate hydrate gel (C-S-H gel) both by direct cement hydration and by secondary reaction of some of the calcium hydroxide generated by cement hydration with the silica-bearing clay particles. It appears, as indicated in Fig. 12A, that such gel acts to bind together individual clay particles and aggregations into a reasonably well knit framework which should resist dispersion

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FIGURE 12A, B

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on raindrop impact. As indicated in Fig. 12B, at least some of the C-S-H gel is the "reticulated network" variety (Diamond, 1970B), found in cement hydration products.

DISCUSSION AND CONCLUSIONS

The results of the erosion tests suggest clearly that lime or cement treatment (involving mechanical mixing, addition of water to near the standard Proctor optimum moisture content and compaction approaching that of the standard Proctor method) can effectively reduce or eliminate raindrop impact-associated erosion loss under severe rainstorm conditions.

The erosion-resistant stabilized soils described in this work had only minimal amounts of stabilizer added to procure the erosion resistance. They are not rendered impermeable, nor do they develop very high mechanical strength.

Highly acidic soils will require relatively large amounts of added stabilizers to overcome the effects of the acidity.

Hydrated lime can be as effective, in practical terms, as Portland cement, provided that a period of several weeks of curing is allowed for between the stabilization and the rainfall. It appears that in difficult situations hydrated lime of a reasonably high quality may be required.

Both hydrated lime and Portland cement applied in inadequate amounts to highly acid soils may act to promote, rather than reduce erosion loss, by raising the pH level sufficiently to destabilize previously existing acid flocculation-bound aggregates, while not at the same time providing the minimum pH level (around 11.5) that seems to be necessary for reaction with the soil particles.

The achievement of erosion resistance is correlateable with development of relatively large water-stable aggregations, and conversely, treated specimens that fail to develop such aggregations undergo erosion loss. It appears that properly stabilized specimens do not undergo significant changes in pore size distribution under the action of the rainfall, even though some material may be eroded away.

The primary stabilizing effect seems to be associated with the development of calcium silicate hydrate gel binding together individual clay particles. Although partial breakdown of some of the clay particles may occur, it is highly unlikely that the extensive decomposition of the clay observed by Mitchell and El Jack (1966) and to some extent by Kawamura et. al. (1970) would occur with the limited levels of cement or lime addition considered here.

The formation of blocky crystals of calcium carbonate seems to occur on exposed surfaces of stabilized soils during the test rainstorm, but it is not though that such crystals contribute significantly to the development of erosion resistance.

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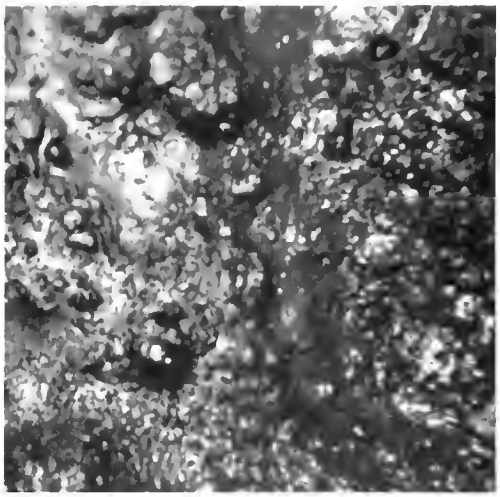
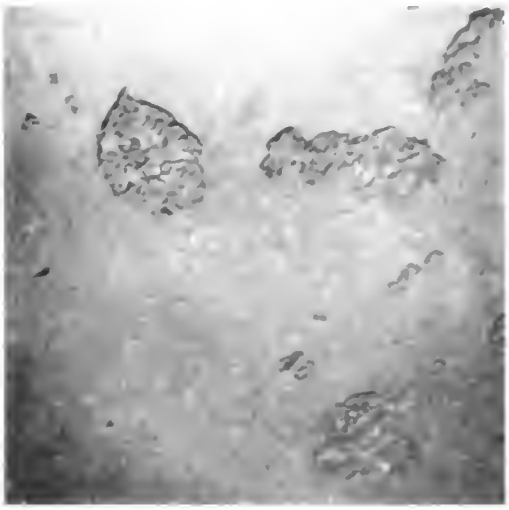
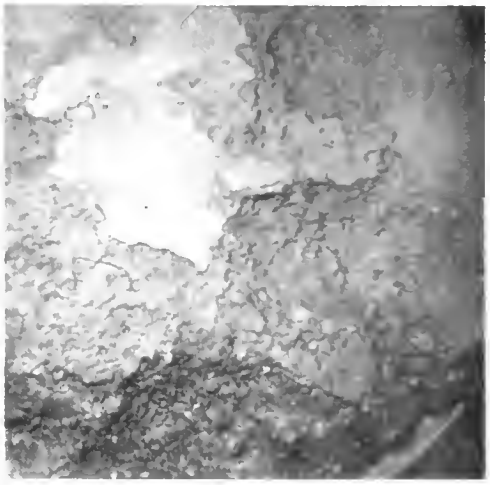


A. Unstabilized Soil



B. Stabilized with 2½ percent Portland cement and cured for 1 day prior to exposure

C. Inadequately stabilized: treated with 1 percent Portland cement and cured for 7 days prior to exposure



D. Stabilized with 2½ percent hydrated lime and cured for 7 days prior to exposure

Figure 1. Appearance of the surfaces of various Crosby soil specimens after exposure to the test rainstorm sequence

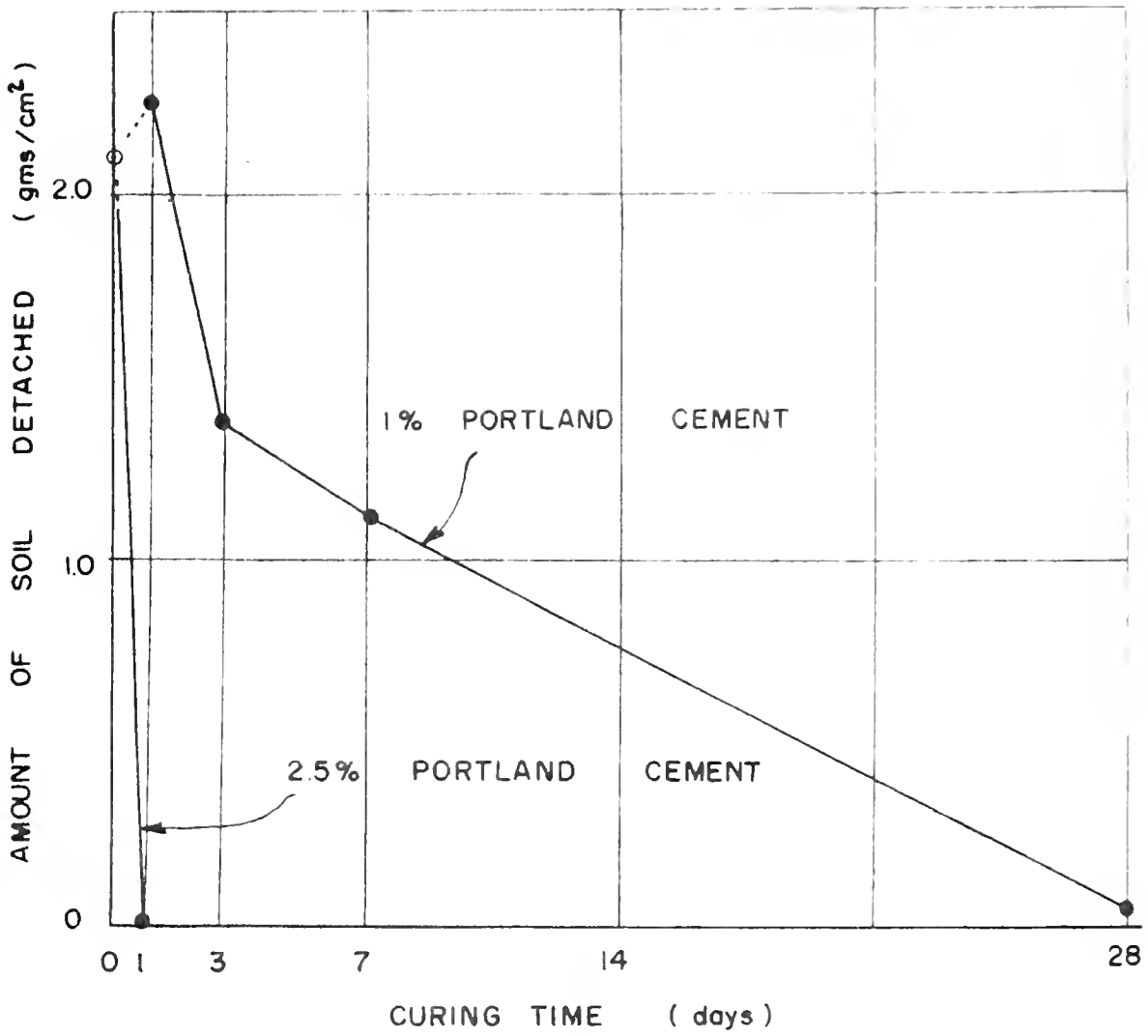


Figure 2. Erosion losses of Portland cement treated Crosby soil specimens as functions of cement level and curing time

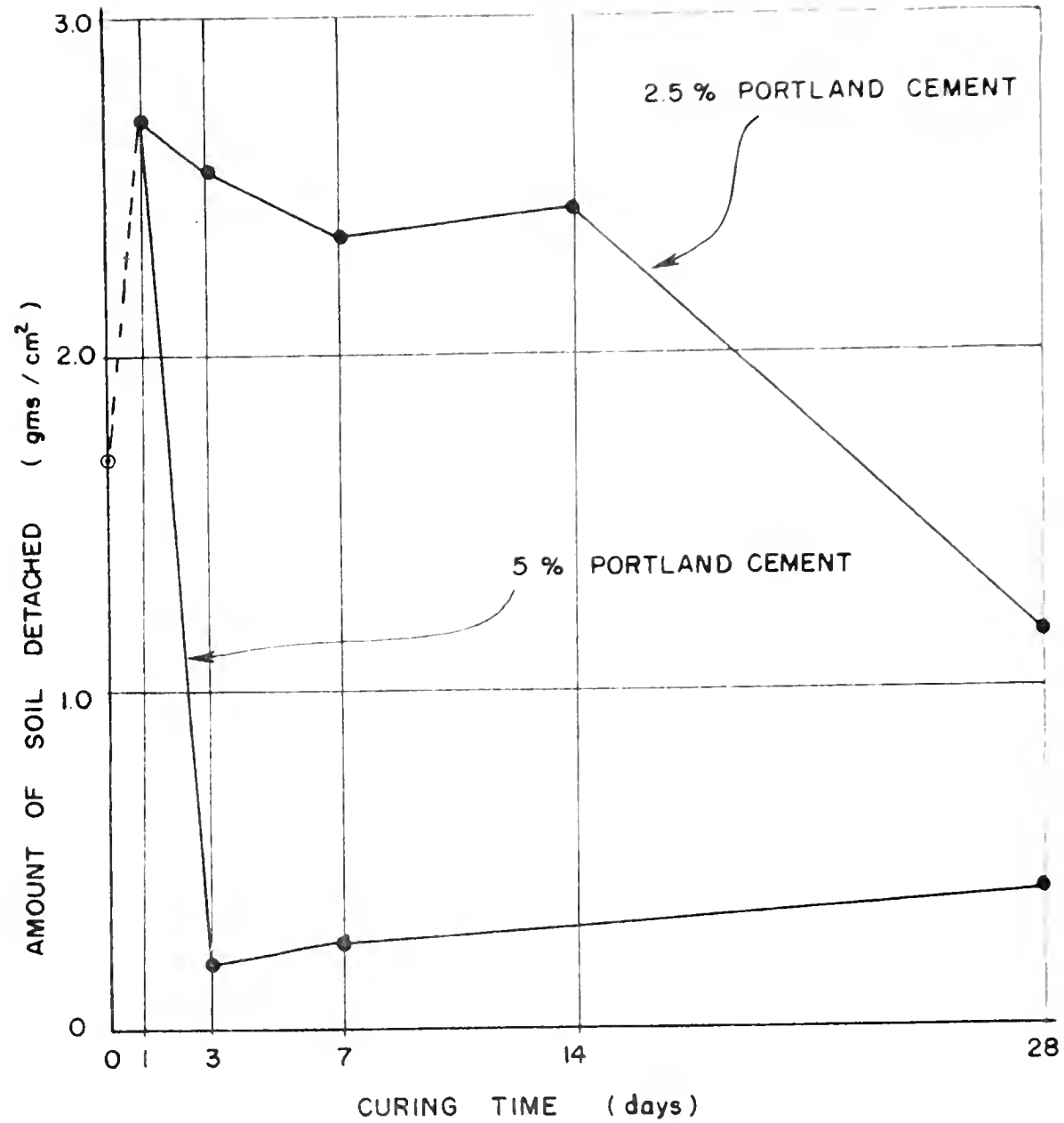


Figure 3. Erosion losses of Portland cement treated grundite clay specimens as functions of cement level and curing time

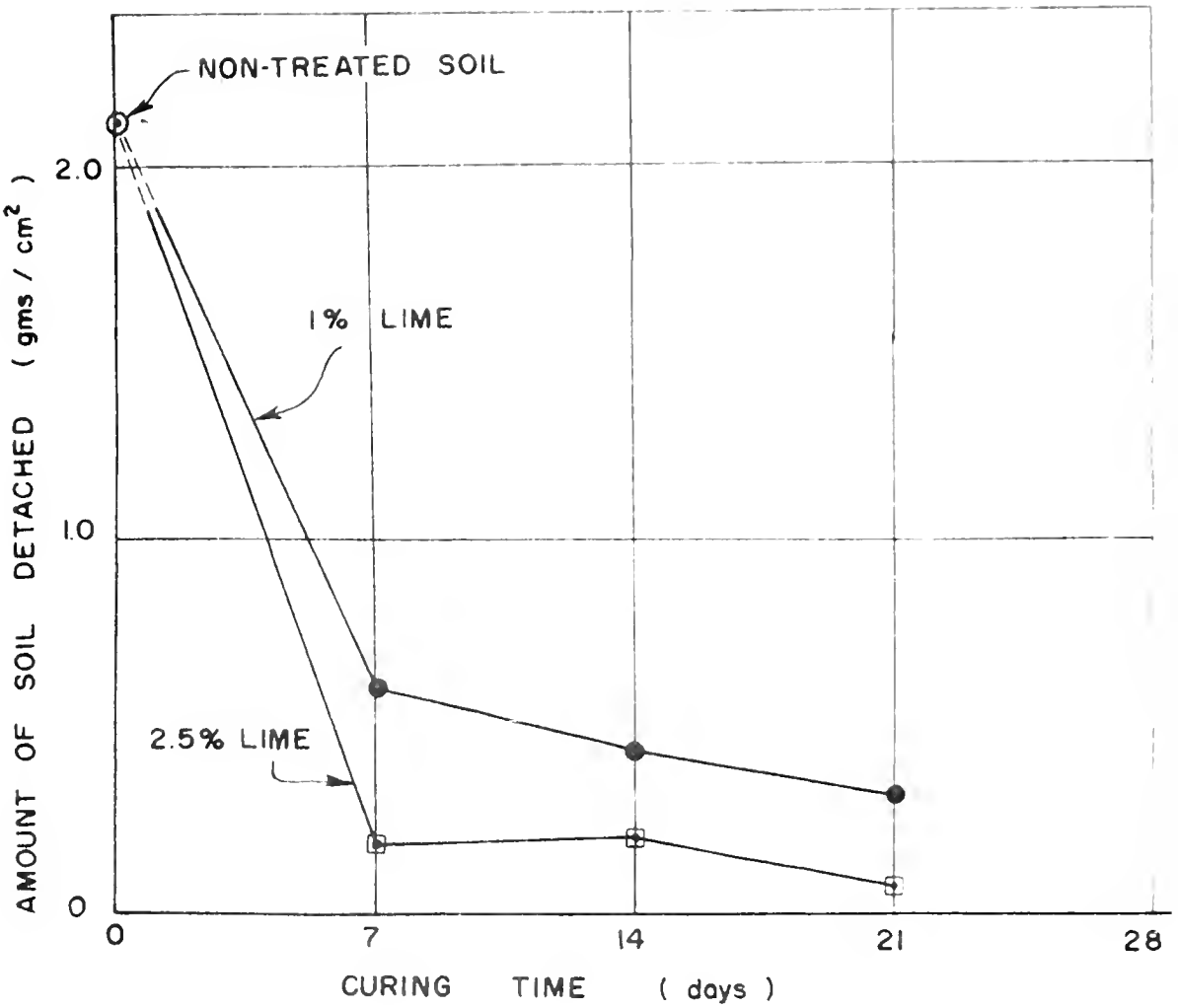


Figure 4. Erosion losses of hydrated lime treated Crosby soil as functions of lime level and curing time

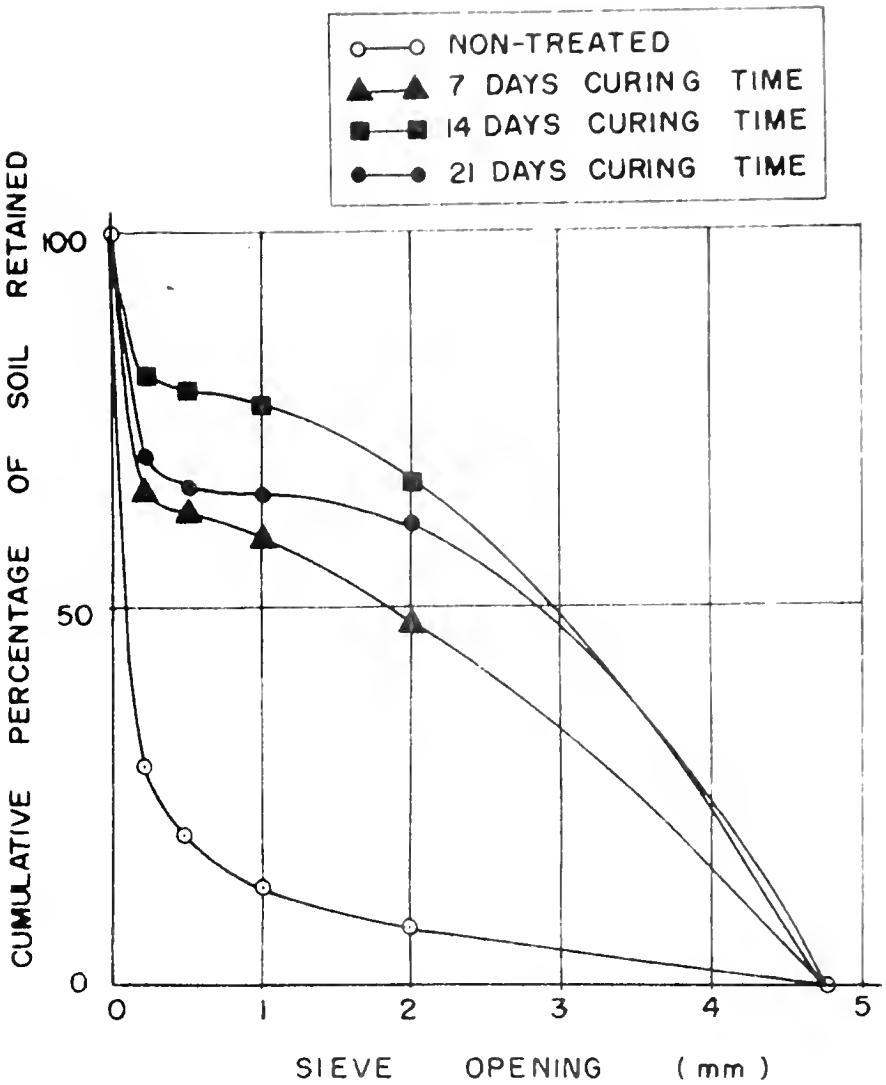


Figure 5. Water-stable aggregate size distributions for Crosby soil treated with 2½ percent hydrated lime and cured for various periods.

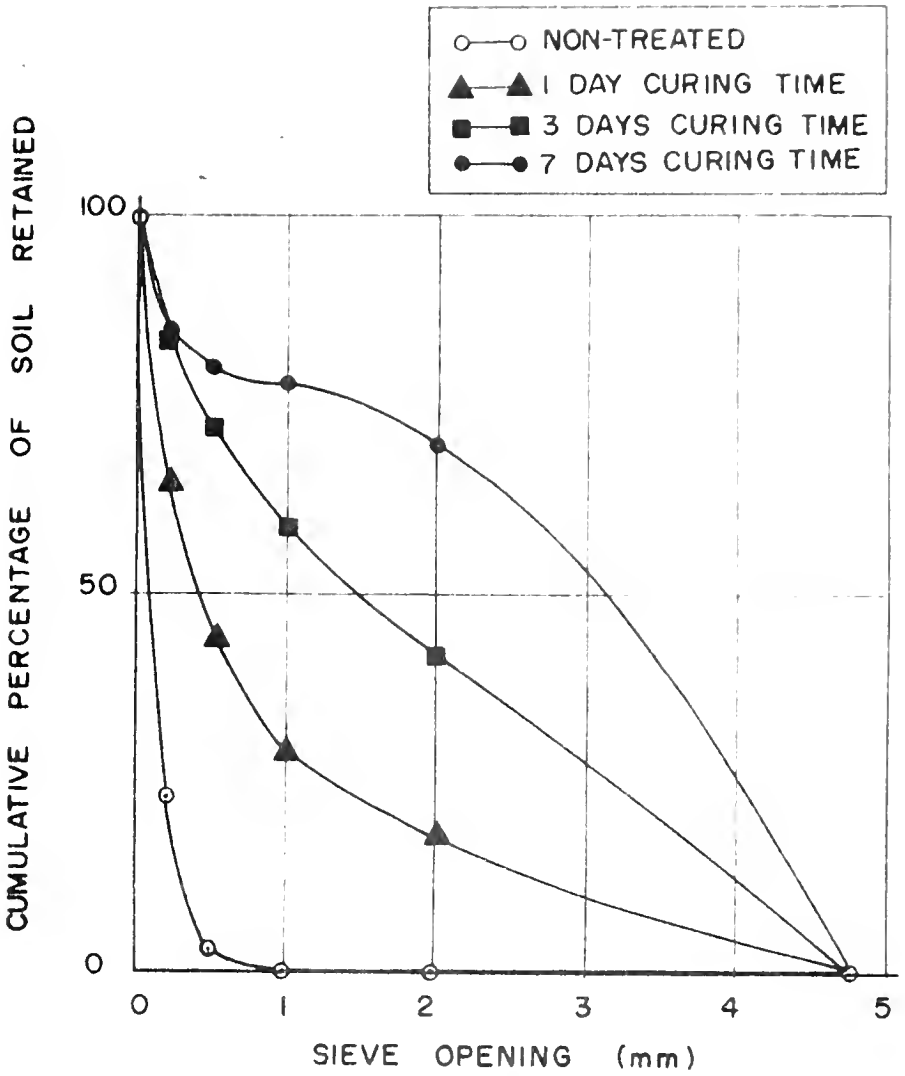


Figure 6. Water-stable aggregate size distributions for grundite clay treated with 5 percent Portland cement and cured for various periods

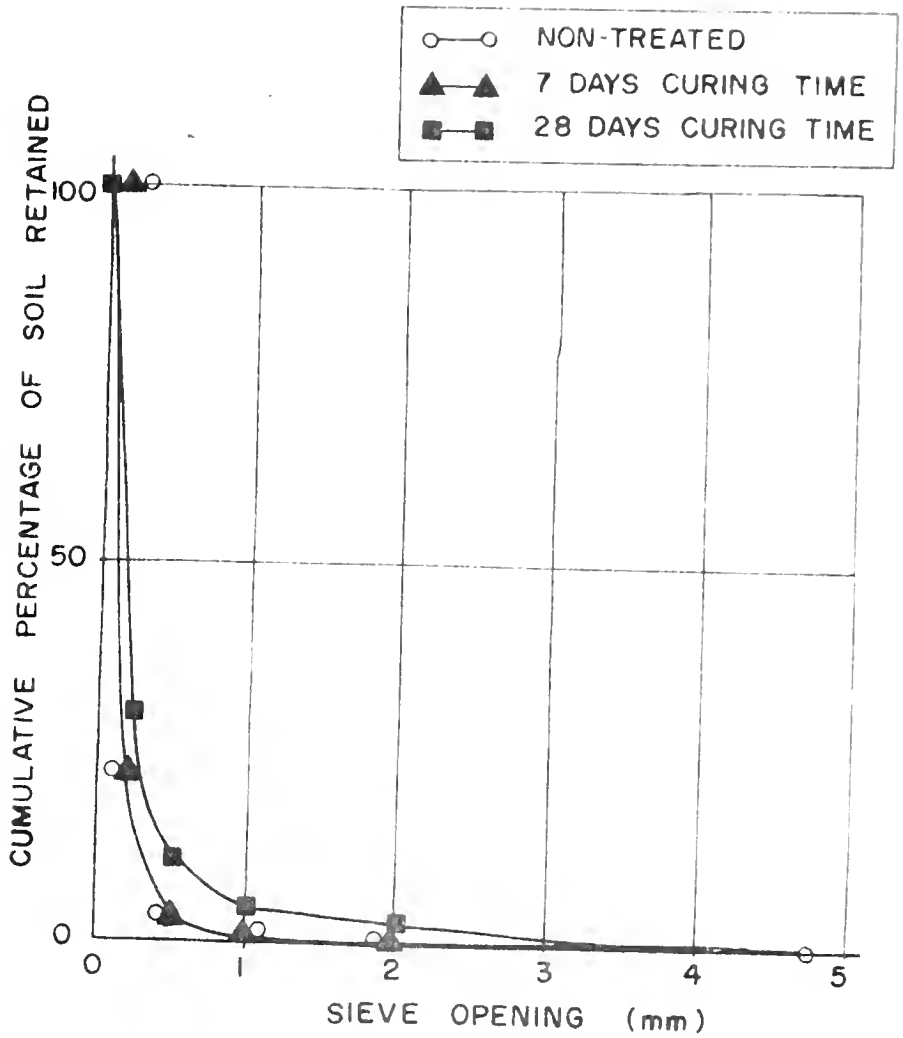


Figure 7. Water-stable aggregate size distributions for grundite clay inadequately treated with 2½ percent Portland cement and cured for various periods

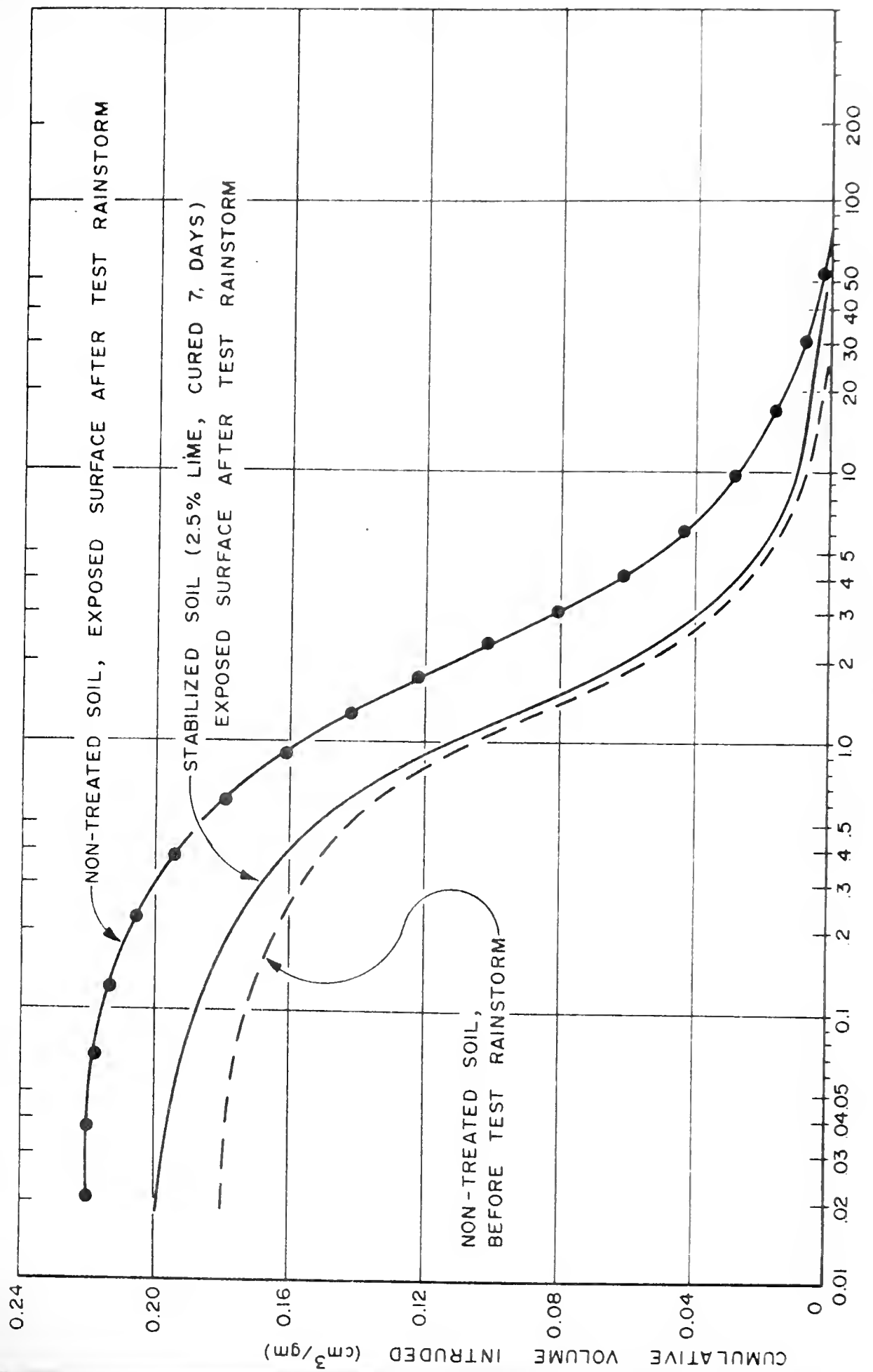


Figure 8. Mercury intrusion pore size distributions for Crosby soil specimens

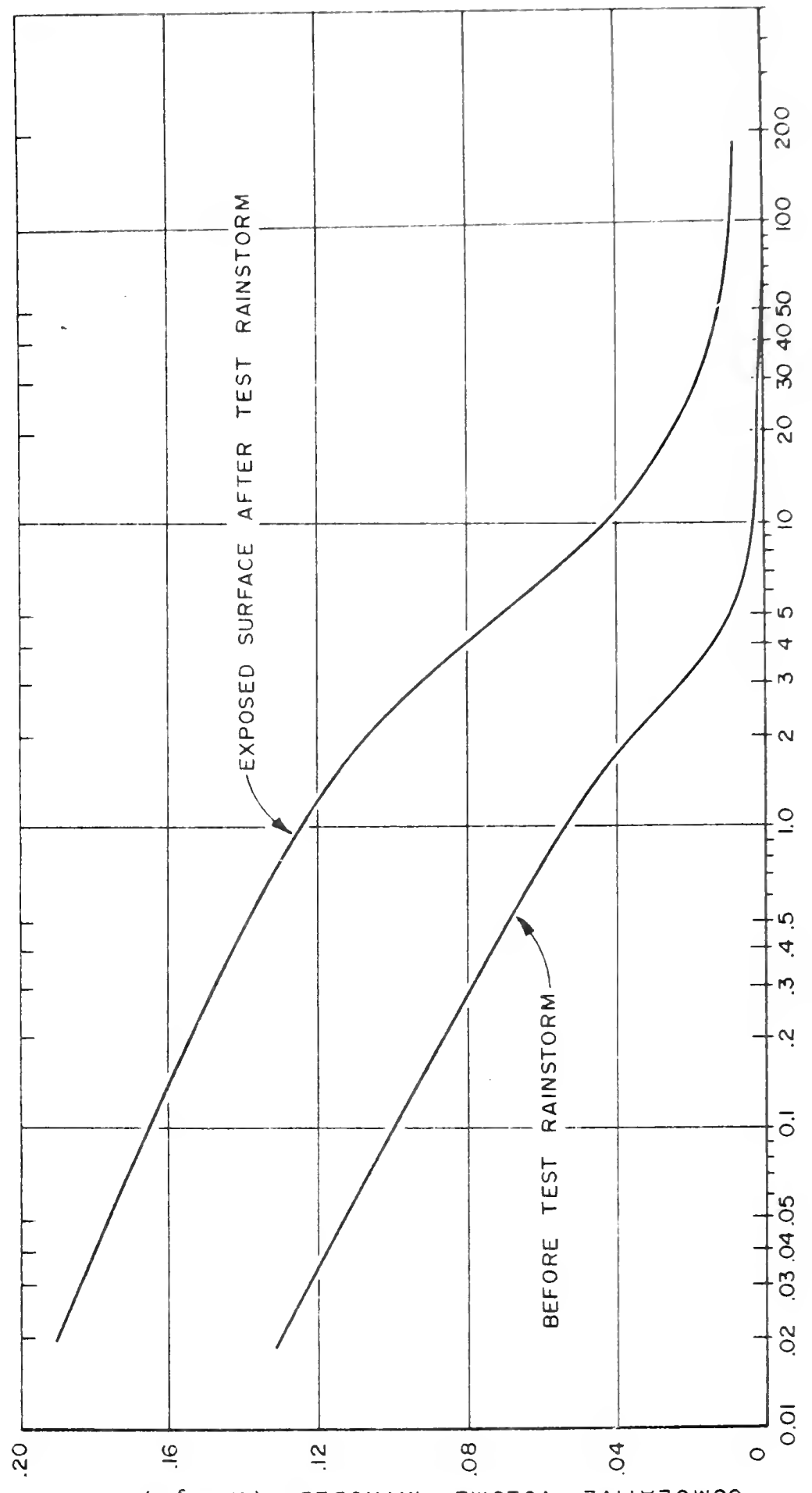
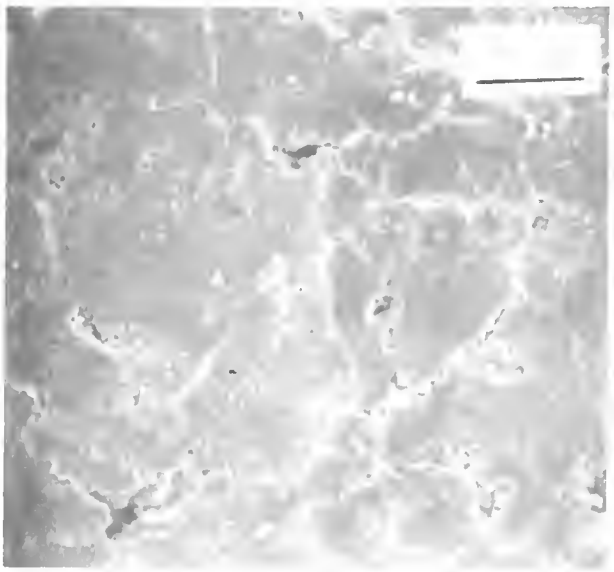
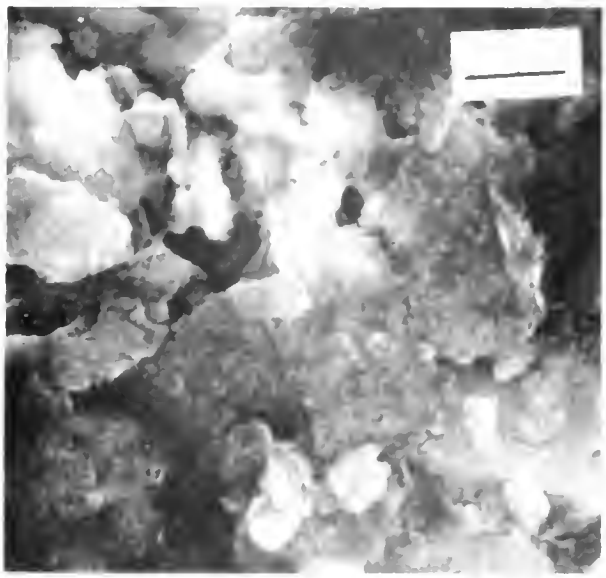


Figure 9. Mercury intrusion pore size distributions for grundite soil inadequately treated with 2½ percent Portland cement and cured for 14 days

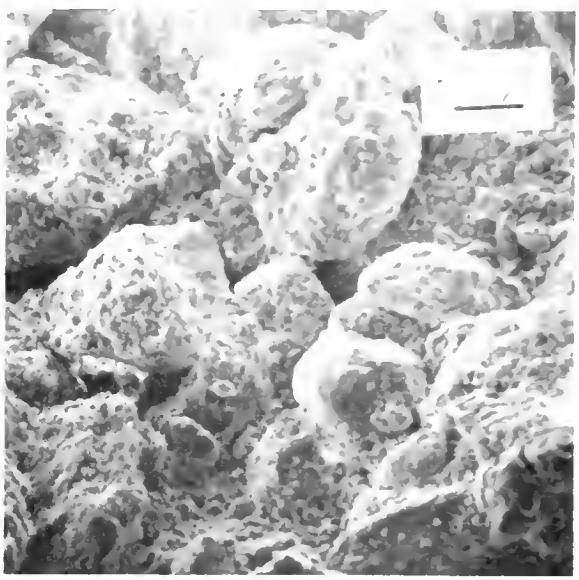


A. Surface of untreated specimen before rainfall exposure, at low magnification



B. High magnification micrograph of a portion of the above showing detail of the oriented clay layer and a region (upper right) of an open area

C. Eroded surface remaining after exposure of the specimen to the rainstorm sequence, showing underlying dispersion-resistant aggregations



D. Residual eroded surface of grundite specimen inadequately treated with 5 percent of impure commercial hydrated lime and cured for 6 days prior to exposure showing partial breakdown of aggregations under raindrop action

Figure 10. Scanning electron micrographs of grundite specimens

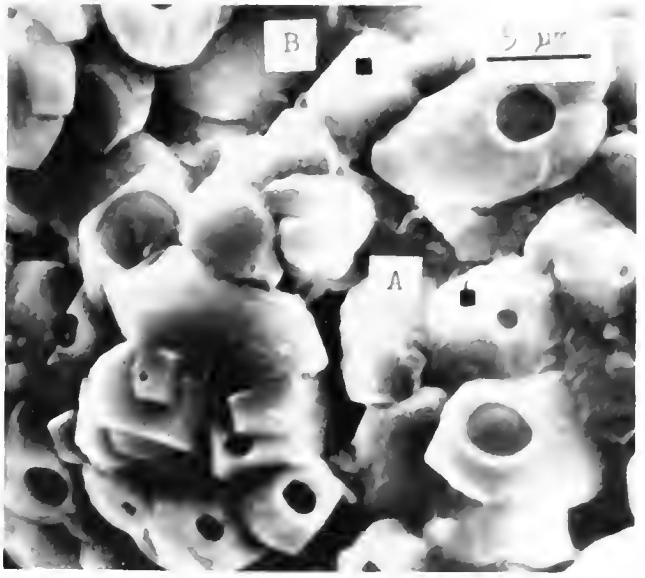


Figure 11. Scanning electron micrograph of residual surface of grundite clay stabilized with 5 percent Portland cement and cured for 7 days before exposure, examined at high magnification

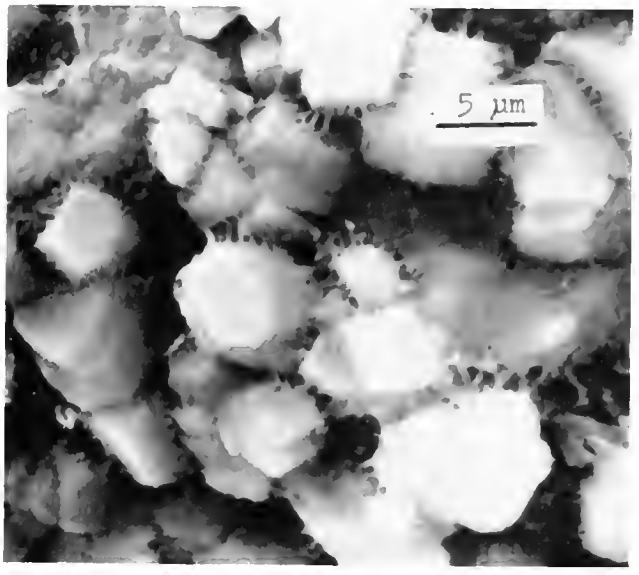


Figure 12A. Scanning electron micrograph of residual surface of grundite clay stabilized with 5 percent Portland cement and cured for 13 days before exposure, showing formation of calcium silicate hydrate gel linking adjacent grains

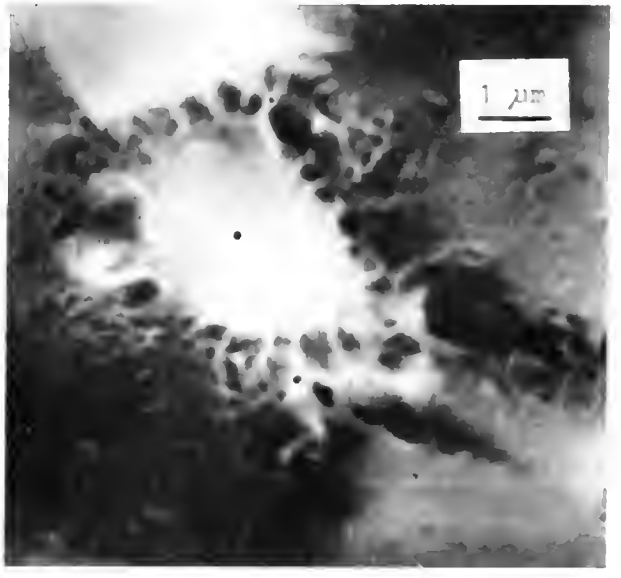


Figure 12B. Higher magnification view of a portion of the above showing the reticulated network structure of the calcium silicate hydrate gel surrounding a clay particle